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The Failure Characteristics of Granite under True Triaxial Unloading Condition

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Abstract

The brittle failure (rock burst) of rock is generally triggered by excavation under high stress in hard rock mass with the characteristics of local violent failure due to a large amount of elastic energy release suddenly around the surrounding opening. For better understanding and monitoring the behavior of hard rock, we have done a series of experiments on samples of Laizhou granite to simulate brittle failure of rock under excavation. Deformation and acoustic emission (AE) were monitored during the tests, which were conducted in a static servo electro-hydraulic controlled true triaxial test machine at a loading rate of 0.5-1.0MPa/s in three directions and an unloading rate of 30MPa/s on one side of the samples. The failure characteristics include thin spalling and slabbing due to tensile stress, blocky fragments with irregular shapes dominated by to shear stress or their coupling effect. The authors observe the slabbing or irregular blocky fragments for granite is closely related to the stress path and the boundary conditions, the higher stress before unloading, the more blocky fragments generated after unloading. The existence of free boundary of the rock mass is of benefit to form slab structure near the opening under a certain stress state to permit the stress redistribution in a period of time. Violent increase of AE events is an indication of rock failure. The testing results are indicative of the failure nature of this granite rock which implies stress mitigation is one method to decrease the disasters caused by brittle failure of rock mass due to excavation in deep underground engineering.

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Keywords: brittle failure; stress path; slabbing and buckling; true triaxial unloading; acoustic emission

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1. Introduction

The brittle rock failure generally induces catastrophic events even including earthquakes[1]. Many brittle failure (or rock burst) of rocks are often triggered by excavation under high stress in hard rock mass due to a large amount of elastic energy release suddenly around the opening, which is different from the failure modes of soft rock with large deformation. The abrupt failure often damages machine, delays construction, and even injures the workers. In China, many disaster events occurred in deep underground rockmass engineering, Such as in tunnelling, underground hydraulic power station and mining, etc.[2,3].

The failure form of brittle rock may be described as spitting due to cracking propagation, collapse caused by gravity in original place and rock burst with the characteristics of blocks with initial ejection velocities. Based on previous research[4-6], the brittle failure of rock occurs at a compressive strength when rapidly loaded under low to moderate confinement, showing a hybrid fracture from extension fracture to shear fracture which can be obtained by triaxial extension experiments, the brittle failure may be explained both with the power spectrum characteristics of sharp onset and high frequency content (predominately 100-300kHz) of acoustic emission event and the sudden increase in cumulative acoustic emission energy. What is more, the quantification of pre-peak brittle damage was also studied through establishing the function of cumulative and the applied load by pure macro-compressive stresses and macro-tensile stresses tests[7].

The failure criterion and mechanism of poly-axial test of intact rock has been researched by Colmenares [8] and Chang[9] under true triaxial compression tests. It is well known the underground excavation is a process with unloading, so some triaxial unloading tests were carried out in the recent decade [10,11].

Regardless of the true triaxial compression or triaxial unloading test, the failure form is either shear fracture or tensile fracture along a localized zone, which is different from the in situ failure modes of slabbing or fragmentation. How about the failure characteristics of rock sample under true triaxial stresses with one side unloading suddenly? We have developed laboratory rock burst test with granite samples using the above method. The results show some failure phenomena which are more similar to what have been observed in the field, such as platy, lentoid blocks, and slabs. The distinction between the new developed test and the conventional tests is that one side can be unloaded suddenly and form a free surface for the sample. The existing of free boundary of the rock mass is of benefit to form the above structural fragments in the vicinity of opening. From this perspective, the prior researches include the crack interaction with free boundary [12], the dynamic model relative to rock delamination [13], the criterion of rock burst with platy failure [14], etc. Here we will show some brittle failure in the true triaxial unloading tests which were not observed obviously in former rock burst tests.

2. True Triaxial Unloading

Six granite samples with the size of 150×60×30mm were tested under true triaxial unloading test machine with the characteristics of loading at three directions(six surfaces) independently and unloading on one surface of the sample suddenly. The test controlling process is shown in Figure 1. The loading rate is about 0.5-1.0MPa/s and the unloading rate about 30MPa/s or higher. In this study, the cycling loading is only designed for the minimum principal stress. A more detailed introduction about the test methods can be found in our preliminary research [15]. The stress state before unloading corresponds to a certain opening depth or engineering status.

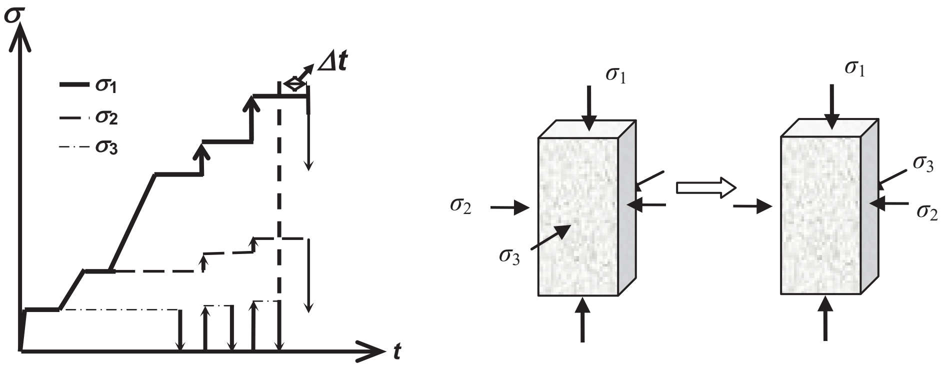
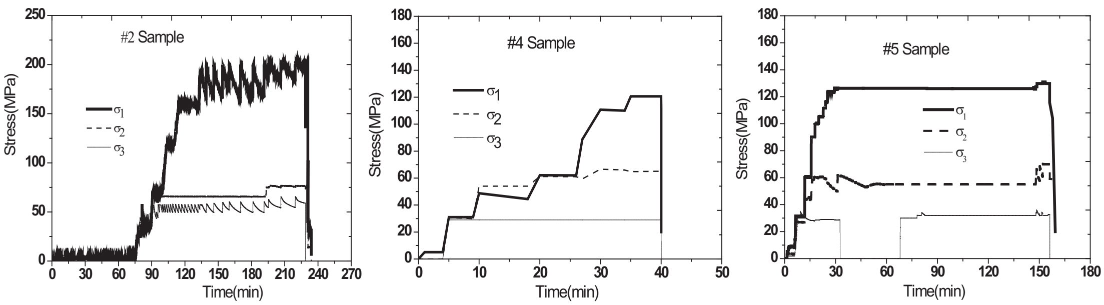


Fig.1. Rock burst test control process

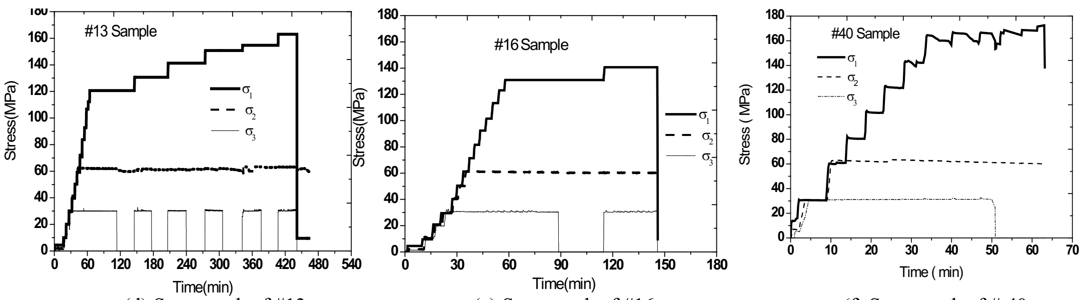
The failure stress states are presented in table 1, including pre-unloading stress states, before failure stresses, and failure modes, etc. The stress paths of the tests on the six samples are shown in Figure2. #2 sample failed under the highest stress, followed by #40, #13, #16, #5 and #4.

Table 1 The test results of granite rock sample

No.	Pre-unloading stress (MPa)	Before failure (MPa)	Failure mode
#2	205/78/60	202/77/0	Small blocks, granular ejection
#4	120/65/29	113/64/0	Platy, arch burst pit
#5	130/70/32	128/67/0	Ejection, Platy spalling
#13	163/63/31	163/63/0	Platy buckling
#16	141/60/31	141/60/0	Splitting buckling
#40	166/61/31	172/60/0	Shear and buckling



(a) Stress path of #2 (b) Stress path of #4 (c) Stress path of #5



(d) Stress path of #13 (e) Stress path of #16 (f) Stress path of # 40

Fig.2 Stresses paths of granite samples

Figure 3, as an example, shows the acoustic emission energy ratio of #40 sample during the test, the higher energy release ratio was monitored after unloading and the peak value was observed just when the main failure was happening. Brittle failure of rock may occur in constant stress level due to rock mass strength reduction gradually caused by cumulative damage. Note the high energy release ratio monitored at the very beginning of the test should be due to noise generated by friction and compaction between steel plate and the sample.

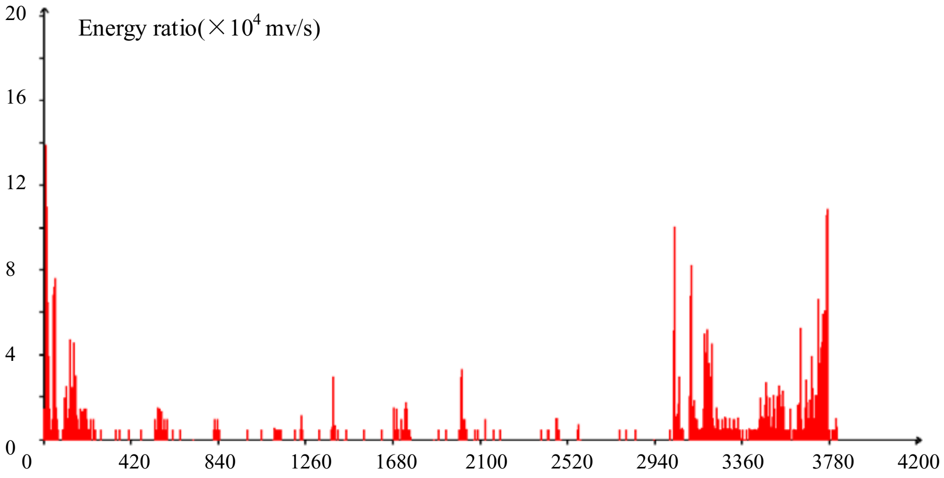


Fig.3 Acoustic emission energy release ratio of #40 sample

The different failure patterns of the samples are exhibited in Figure 4. We can observe the entirely ruptured blocks of #2 sample under higher failure stress state, the rock burst arch pit of #4 sample under lower failure stress state, the platy or granular ejection and buckling of #13, #16 and # 40 and the granular and platy fragments ejection of #5 falling in front of specimen.

The rock samples show distinct failure characteristics under different stress state after unloading on one surface suddenly. The results imply that the stress states is the main factor on the brittle failure of this granite,i.e., the higher stress state, the more small blocks generated in a whole sample during failure. Sub-high stress state corresponded with local buckling. Platy spalling and grains ejection generated in low stress level. The acoustic emission energy release ratio rapidly increased after unloading suddenly and before failure. To some extent, the stress mitigation slowly should be a good method to control brittle failure for underground excavation engineering in hard rockmass, aiming at decreasing stress level and controlling the violence of rock failure.

(a) #2 (b) #4 (c) #5 (d) #13 (e) #16 (f) #40

Fig.4 Samples after failure

3. Conclusions

The distinct failure modes are described based on the true triaxial unloading suddenly test results. The failure characteristics of samples are more similar to in situ rock burst, including platy fragment, terrace buckling and arch cracking plane, etc. AE monitoring showed that AE energy ratio increased rapidly with crack propagation and interaction due to sudden unloading and stress redistribution in the sample. The stress path is a main factor controlling rock failure forms. The results may have enlightened influence on guiding underground excavation in hard rock.

4. Acknowledges

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References

[1] André Moura, Xinglin Lei, Osamu Nishisawa. “Prediction scheme for the catastrophic failure of highly loaded brittle materials or rocks”. *Journal of the Mechanics and Physics of Solids*, 2005;Vol.53, p.2435-2455.

[2] He M C. Rock Mechanics and Hazard Control in Deep Mining Engineering in China. ISRM International Symposium. 4th Asian Rock Mechanics Symposium. Rock Mechanics in Underground Construction. 8－10 November 2006，Singapore：p.29－46.World Scientific Publishing Co. Pte. Ltd. NEW JERSEY. LONDON. SINGAPORE. BEIJING etc.

[3] Wu Xuan-zheng, LI Ming-chuan, WUYu-ten. “Analysis and prevention measures for rock-burst in the auxiliary tunnel of the JinpingHydropower State”. *Journal of Shandong University*(*Engineering Science*). 2008, Vol.**38**(3), p 28-33.

[4] Carl E. Renshaw, Erland M. Schulson. “Universal behaviour in compressive failure of brittle materials”. *Nature*, 2001; 412: p.897-900.

[5] Jonathan M. Ramsey, Frederick M. Chester. “Hybrid fracture and the transition from extension fracture to shear fracture”. *Nature*, 2004;428:p. 63-66.

[6] Hugh Tuffen, Rosanna Smith and Peter R. Sammonds.. “Evidence for seismogenic fracture of silicic magma”. *Nature*, 2008;453:p. 511-514.

[7] P.Ganne, A. Vervoort, M.Wevers. "Quantification of Pre-peak brittle damage: Correlation between acoustic emission and observed micro-fracturing". *International Journal of Rock Mechanics and Mining Sciences*. .2007; 44: p.720-729.

[8] L.B.Colmenares, M.D.Zoback. " A statistical evaluation of intact rock failure criteria constrained by polyaxial test data for five different rocks". *International Journal of Rock Mechanics and Mining Sciences*. 2002;39: p.695-729.

[9] C. Chang, B. Haimson. " Non-dilatant deformation and failure mechanism in two Long Valley Caldera rocks under true triaxial compression". *International Journal of Rock Mechanics and Mining Sciences*. 2005; 42: p.402-414.

[10] Xu linsheng. "Research on the experimental rock mechanics of rock burst under unloading condition". *Journal of Chongqing jiaotong university*. 2003; Vol 22(1):p.1-4.

[11] Jiang laifeng. "Study on predection and prevention of rock burst in Anlu tunnel". Xinanjiaotong university, *Engineering master thesis.*2008.

[12] A.V. Dyskin, L.N.Germanovich, K.B.Ustinov. " Asymptotic analysis of crack interaction with free boundary". *International Journal of Rock Mechanics and Mining Sciences*. 2000;37: p.857-886.

[13] J.F. Hazzard, R.P. Young. " Dynamic modelling of induced seismicity". *International Journal of Rock Mechanics and Mining Sciences*. 2004;41: p.1365-1376.

[14] Wang Minqiang, Hou Faliang. (1993). " A method to determine rock burst in rockmass with plate-form damage". *Rock and soil mechanics.* 1993;Vol 14(3):p. 53-60.

[15] He MC, Miao JL, Li DJ, et al.. "Experimental study on rock burst processes of granite specimen at great depth". *Chinese Journal of Rock Mechanics and Engineering*. 2007; Vol 26 (5): p.865-876.